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Control for hybrid combined cycle with parabolic trough and molten-salt storage

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Abstract: This paper deals with *Hybrid Combined Cycles* (HCC) and their control in a way that optimizes system behavior. It first presents an HCC dynamical model, resulting from the coupling of a Combined Cycle Power Plant, a linear solar concentrator and a thermal storage. The global HCC model is proven to be observable and controllable. It is used to develop two control strategies: decentralized and coordinated. Both are compared by means of simulations. The coordinated control shows an efficient use of the solar and the storage subsystems.

Keywords: Hybrid Combined Cycle, Decentralized control, Coordinated control

1. INTRODUCTION

Today, production optimization and global warming have become pressing issues that need to be tackled. In this context, flexible energy production is important. A Combined Cycle Power Plant (CCPP) is an example of a flexible plant. At the same time, combining a CCPP with a solar plant allows to reduce pollutant emissions. A storage system can be added to ensure an optimal daily production. The resulting plant consisting of a CCPP, a solar and a storage system is called a Hybrid Combined Cycle (HCC).

This paper treats the control of such a HCC configuration. On the one hand, related works present a system that combines a CCPP and a solar system (Rovira et al. (2013)). On the other hand, the system that couples a storage and a solar part has been widely studied (Rodríguez et al. (2013)). However, to the authors knowledge, there is no study that presents a system combining a CCPP, a solar and a storage part. The aim of the present study is to propose a dynamical model for this specific configuration of an HCC and to synthesize an optimal control. It is interesting to coordinate the three HCC subsystems by a *supervisory* control that takes into account dependencies between each subsystem. The global aim is to reduce fuel consumption in the gas turbine but also to be more flexible when a power demand occurs. Notice that some studies have developed controls on CCPP (Kehlhofer et al. (2009), Tică et al. (2012)), on solar systems (Camacho et al. (2007a), Camacho et al. (2007b)) or on storage systems (Ma et al. (2009)) separately. The idea here is to combine the controls of each subsystem in a decentralized or in a coordinated way, as in (Zarate-Florez (2012), Leo et al. (2015)).

The structure of the paper is as follows. Section II describes the three subsystems, the coupled system (HCC) and the resulting model. Then, section III proposes two control designs: decentralized and coordinated. Simulation results are presented and discussed in section IV. At last, section V concludes the paper.

2. STUDIED SYSTEM

In this work, the modelled Hybrid Combined Cycle power plant (HCC) is a combination of a Combined Cycle Power Plant, a solar installation and a storage system.

2.1 Combined Cycle Power Plant system

The concept of a CCPP is that after the Gas Turbine (GT - Topping or Brayton cycle) completes its cycle, the working fluid is still able to provide heat energy to the working fluid of the Steam Turbine (ST - Bottoming or Rankine cycle). The GT hot exhaust gases pass through the Heat Recovery Steam Generator (HRSG) to preheat, evaporate and superheat the ST water. Combining these two thermodynamic cycles improves the overall efficiency and reduces fuel costs (Fig. 1).

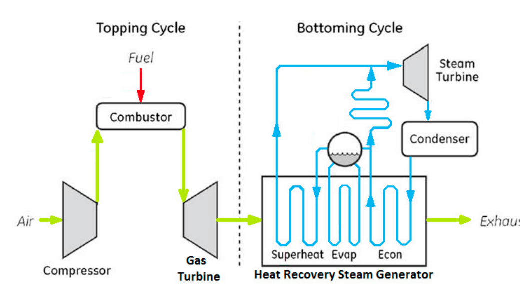

Fig. 1. Combined Cycle Power Plant (CCPP)

An actual CCPP, located in the south of France, is considered in this study. The basic design parameters

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and the control parameters are included in the model to represent the behavior of the real plant (Tică et al. (2012)). The considered nonlinear model contains about 200 variables including temperatures, pressures, enthalpies and tank levels.

2.2 Solar system

The solar technology chosen for coupling with the CCPP is a linear concentrator solar system. In these systems, the solar radiation is concentrated by reflectors onto a receiver tube in order to heat a Heat Transfer Fluid (HTF). Four types of linear concentrator solar systems can be pointed out (Kalogirou (2004), Sylvain (2007)): Parabolic Trough (PT), dish stirling, Linear Fresnel Reflector or solar Tower plant. In this study, a PT solar system is selected because of its widespread employment and its efficiency. Compared to the other linear concentrator solar system, the PT solar system uses oil HTF to extract heat energy from the solar radiation. Then, the oil HTF transfers this energy to the water HTF in a heat exchanger. The water HTF flowing inside the heat exchanger cold side is heated by the oil HTF until evaporation and superheated thereafter (Fig. 2).

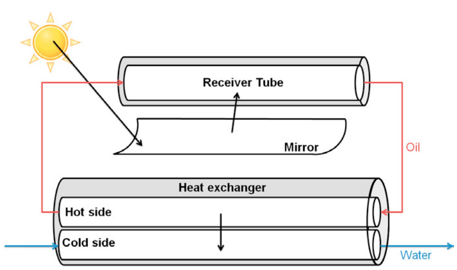

Fig. 2. Solar Parabolic Trough Reflector (PT)

Similarly to the CCPP system, the basic design parameters and the control parameters are included in the model to represent the behavior of the classical plant (Leo et al. (2014)). The considered nonlinear model contains about 50 variables including flows, temperatures, pressures and enthalpies of the oil HTF and of the water HTF.

2.3 Storage system

An efficient storage technology used for coupling linear concentrator solar systems is thermal energy storage. In these systems, heat can be stored and released when it is needed. Different types of thermal energy storage system can be pointed out: direct or indirect storage system using one tank or two tanks for example (Pintaldi et al. (2015), Gil et al. (2010), Medrano et al. (2010)). In this study, a molten-salt two-tank indirect storage system is selected because of its widespread deployment and its low cost. Compared to other thermal energy storage systems, the selected system uses molten-salt HTF to transport energy, from a cold storage tank to a hot storage tank in charging mode, or inversely in discharging mode. Then, the molten-salt HTF exchanges this thermal energy with the oil HTF in a heat exchanger (Fig. 3).

Similarly to the other two systems, the basic design parameters and the control parameters are included in the model to represent the behavior of the plant inspired

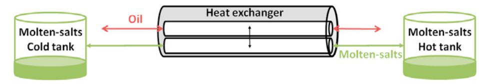

Fig. 3. Molten-salt two-tank indirect storage

from (Rodríguez et al. (2013)). The considered nonlinear model contains about 20 variables including temperatures, pressures, enthalpies and tank levels of the oil HTF and the molten-salt HTF.

2.4 Global system

The global system corresponds to a innovative coupling between CCPP, solar system and storage system. The solar system is used in the Rankine cycle of the CCPP to evaporate the water HTF. This HTF is extracted from the HRSG after preheating. Then, it is evaporated in the solar system concurrently to the part which is heated in the HRSG by the hot exhaust gases. Eventually, the steam HTF is injected into the high pressure superheater of the HRSG. The storage system is used in the solar cycle to store additional heat and refurnish it when it is necessary. The coupling is made thanks to heat exchangers between the oil HTF of the solar cycle and the molten-salt HTF of the storage cycle (Fig. 4). This global system, that is called an hybrid combined cycle, does not exist yet. But this is a combination of two existing systems : an integrated solar combined cycle (CCPP and solar part) and a concentrated solar plant with a storage system.

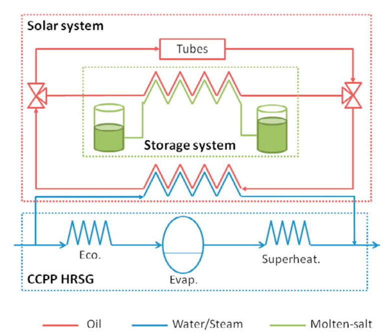

Fig. 4. Global system

The resulting HCC model consists of three subsystems. Each subsystem consists of a physical model obtained by the integration of the conservation laws and a local control that completes a control goal. Let us consider the case of n coupled subsystems where subsystem i is denoted by S_i. The following variables are used (with $j \neq i$, referring to subsystem S_j):

- Setpoints of control laws, which can be considered as tunable variables, gathered in a vector c_i;
- Disturbances, denoted by p_i;
- Coupling variables between system i and system j, corresponding to a coupling input vector d_{ij} and output vector y_{ij}^d;
- State variables, collected in x_i;
- Output variables to be controlled, corresponding to y_{ij}^d and possibly some y_{ii}, aggregated into a vector y_i.

A linear model of S_i is calculated around several equilibrium points by linearization of the nonlinear model and takes the following form: